

Triton- ^3He relative and differential flows as probes of the nuclear symmetry energy at supra-saturation densities

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Using a transport model coupled with a phase-space coalescence after-burner we study the triton- ^3He ratio, relative and differential transverse flows in semi-central $^{132}\text{Sn} + ^{124}\text{Sn}$ reactions at a beam energy of 400 MeV/nucleon. The neutron-proton ratio, relative and differential flows are also discussed as a reference. We find that similar to the neutron-proton pairs the triton- ^3He pairs also carry interesting information about the density dependence of the nuclear symmetry energy. Moreover, the nuclear symmetry energy affects more strongly the t- ^3He relative and differential flows than the π^-/π^+ ratio in the same reaction. The t- ^3He relative flow can be used as a particularly powerful probe of the high-density behavior of the nuclear symmetry energy.

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I. INTRODUCTION

The density dependence of nuclear symmetry energy especially at supra-saturation densities is among the most uncertain properties of neutron-rich nuclear matter[1, 2]. However, it is very important for nuclear structure[3, 4], heavy-ion reactions[5, 6, 7, 8, 9, 10] and many phenomena/processes in astrophysics and cosmology [11, 12, 13]. Heavy-ion reactions especially those induced by radioactive beams provide a unique opportunity to constrain the symmetry energy at supra-saturation densities in terrestrial laboratories. Various probes using heavy-ion reactions have been proposed in the literature, see, e.g., ref.[10] for the most recent review. It is particularly interesting to mention that, besides many significant results about the symmetry energy at sub-saturation densities, see, e.g., refs.[14, 15, 16, 17, 18, 19, 20], circumstantial evidence for a rather soft symmetry energy at supra-saturation densities has been reported very recently[21] based on the IBUU04 transport model[22] analysis of the π^-/π^+ data taken by the FOPI Collaboration at SIS/GSI[23]. However, many interesting issues remain to be resolved. Thus, to constrain tightly and reliably the nuclear symmetry energy especially at supra-saturation densities, much more efforts by both the nuclear physics and the astrophysics communities are still needed.

In the present work, we have the following two main purposes. Firstly, there is an urgent need to verify the conclusion about the soft symmetry energy at supra-saturation densities required to reproduce the FOPI π^-/π^+ data within transport model analyses[21, 23]. It is better if this test can be done with not only more π^-/π^+ data but also other sensitive observables

in the most neutron-rich reactions possible. We will thus make predictions using the same transport model[22] for doing this test. Secondly, it was predicted that the neutron-proton differential flow is another sensitive probe of the high-density behavior of the nuclear symmetry energy[24]. However, it is difficult to measure observables involving neutrons. One question often asked by some experimentalists is whether the triton- ^3He pair may carry the same information as the neutron-proton one. We will try to answer this question quantitatively by coupling the IBUU04 calculations to a phase-space coalescence after-burner. Indeed, we found that, similar to the neutron-proton pair, the triton- ^3He relative and differential transverse flows are sensitive to the high-density behavior of the nuclear symmetry energy. They can be used to test indications about the high-density behavior of the symmetry energy observed earlier from analyzing the π^-/π^+ data.

II. SUMMARY OF THEORETICAL MODELS

Our study is carried out based on the IBUU04 version of an isospin and momentum dependent transport model and the simplest phase-space coalescence after-burner. For completeness and consistency we recall here a few major features of the IBUU04 transport model most relevant to the present study. More details of the model can be found in Refs. [22]. The single nucleon potential is one of the most important inputs to BUU-like transport models for nuclear reactions. In the IBUU04 transport model, we use a single nucleon potential derived within the Hartree-Fock approach using a modified Gogny effective interaction (MDI) [25], i.e.,

$$\begin{aligned}
U(\rho, \delta, \mathbf{p}, \tau) = & A_u(x) \frac{\rho_{\tau'}}{\rho_0} + A_l(x) \frac{\rho_{\tau}}{\rho_0} + B \left(\frac{\rho}{\rho_0} \right)^{\sigma} (1 - x\delta^2) - 8x\tau \frac{B}{\sigma + 1} \frac{\rho^{\sigma-1}}{\rho_0^{\sigma}} \delta \rho_{\tau'} \\
& + \frac{2C_{\tau, \tau'}}{\rho_0} \int d^3 \mathbf{p}' \frac{f_{\tau}(\mathbf{r}, \mathbf{p}')}{1 + (\mathbf{p} - \mathbf{p}')^2 / \Lambda^2} + \frac{2C_{\tau, \tau'}}{\rho_0} \int d^3 \mathbf{p}' \frac{f_{\tau'}(\mathbf{r}, \mathbf{p}')}{1 + (\mathbf{p} - \mathbf{p}')^2 / \Lambda^2}.
\end{aligned} \tag{1}$$

Here $\delta = (\rho_n - \rho_p)/\rho$ is the isospin asymmetry of the nuclear medium. In the above $\tau = 1/2$ ($-1/2$) for neutrons (protons) and $\tau \neq \tau'$; $\sigma = 4/3$; $f_{\tau}(\vec{r}, \vec{p})$ is the phase space distribution function at coordinate \vec{r} and momentum \vec{p} . The parameter x was introduced to mimic predictions on the density dependence of symmetry energy $E_{\text{sym}}(\rho)$ by microscopic and/or phenomenological many-body theories. The parameters $A_u(x)$ and $A_l(x)$ depend on the x parameter according to

$$A_u(x) = -95.98 - x \frac{2B}{\sigma + 1}, \quad A_l(x) = -120.57 + x \frac{2B}{\sigma + 1}. \tag{2}$$

The coefficients in $A_u(x)$ and $A_l(x)$ and the parameters $B, C_{\tau, \tau}, C_{\tau, \tau'}$ and Λ were obtained by fitting the momentum-dependence of the $U(\rho, \delta, \vec{p}, \tau, x)$ to that predicted by the Gogny Hartree-Fock and/or the Brueckner-Hartree-Fock (BHF) calculations, the saturation properties of symmetric nuclear matter and the symmetry energy of about 31.6 MeV at normal nuclear matter density $\rho_0 = 0.16 \text{ fm}^{-3}$. The incompressibility K_0 of symmetric nuclear matter at ρ_0 is set to be 211 MeV consistent with the latest conclusion from studying giant resonances [25].

The last two terms in Eq. (1) contain the momentum-dependence of the single-particle potential. The momentum dependence of the symmetry potential stems from the different interaction strength parameters $C_{\tau, \tau'}$ and $C_{\tau, \tau}$ for a nucleon of isospin τ interacting, respectively, with unlike and like nucleons in the background fields. More specifically, we use $C_u \equiv C_{\text{unlike}} = -103.4$ MeV and $C_l \equiv C_{\text{like}} = -11.7$ MeV. With these parameters, the isoscalar potential estimated from $(U_{\text{neutron}} + U_{\text{proton}})/2$ agrees reasonably well with predictions from the variational many-body theory [22, 26]. At the normal nuclear matter density ρ_0 , it is consistent with the isoscalar nucleon optical obtained from the nucleon-nucleus scattering experiments [22]. The strengths of the corresponding isovector (symmetry) potential can be estimated from $(U_n - U_p)/2\delta$. At ρ_0 , by design, the symmetry potential is independent of x and is consistent with the Lane potential extracted from the nucleon-nucleus scattering experiments and the (p,n) charge exchange reactions [10].

The corresponding MDI symmetry energy can be written as [27]

$$\begin{aligned}
E_{\text{sym}}(\rho) = & \frac{8\pi}{9m\hbar^3\rho} p_f^5 + \frac{\rho}{4\rho_0} [-24.59 + 4Bx/(\sigma + 1)] - \frac{Bx}{\sigma + 1} \left(\frac{\rho}{\rho_0} \right)^{\sigma} \\
& + \frac{C_l}{9\rho_0\rho} \left(\frac{4\pi}{\hbar^3} \right)^2 \Lambda^2 \left[4p_f^4 - \Lambda^2 p_f^2 \ln \frac{4p_f^2 + \Lambda^2}{\Lambda^2} \right] + \frac{C_u}{9\rho_0\rho} \left(\frac{4\pi}{\hbar^3} \right)^2 \Lambda^2 \left[4p_f^4 - p_f^2 (4p_f^2 + \Lambda^2) \ln \frac{4p_f^2 + \Lambda^2}{\Lambda^2} \right],
\end{aligned} \tag{3}$$

where $p_f = \hbar(3\pi^2 \frac{\rho}{2})^{1/3}$ is the Fermi momentum for symmetric nuclear matter at density ρ .

The IBUU04 model can use either the experimental nucleon-nucleon (NN) cross sections or the in-medium NN cross sections calculated using an effective-mass scaling model consistent with the single particle potential used [15]. In the present work the in-medium NN cross sections are used. The isospin-dependent Pauli blocking has been implemented by evolving and checking explicitly neutron and proton phase-space distributions separately. The coordinates of nucleons in the colliding nuclei are initialized randomly according to the neutron/proton density profiles predicted by the Skyrme-Hartree-Fock approach. The corresponding Fermi momenta are calculated using the local Thomas-Fermi ap-

proximation. The initial state generated in such way is rather stable for several hundred fm/c without appreciable particle emission in evolving a single nucleus with a momentum-independent mean-field. However, as it is widely known, see, e.g., ref. [28], momentum dependent mean-field makes the initial state less stable. For instance, in evolving a single ^{124}Sn nucleus with the IBUU04, at 40 fm/c (by which most of the nucleons should have freezed-out in heavy-ion reactions at a beam energy of 400 MeV/nucleon) the average ratios of emitted/initial protons and neutrons are 0.6/50 and 1.7/74, respectively, in calculations using 600 test-particles per nucleon. The ratios go up to about 1.5/50 and 3.4/74, respectively, in calculations using 200 test-particles per nucleon. Our results presented in the following are ob-

tained using totally 10,000 events in each case by using 200 test-particles per nucleon in each run of the simulation.

Because most BUU-type transport models including the IBUU04 are incapable of forming dynamically realistic nuclear fragments, some types of after-burners, such as statistical and coalescence models, are normally used as a remedy. This kind of hybrid models can be used to study reasonably well, for instance, nuclear multifragmentation, see, e.g., ref.[29, 30, 31, 32], collective flow of light fragments, see e.g., [33, 34, 35] and the formation of hypernuclei[36]. There are, however, some remaining issues, such as the freeze-out time of fragments that is related to the time of coupling the transport model with the after-burner, etc. There are also interesting work in using advanced coalescence models[37, 38], see, e.g., refs.[39, 40]. We notice here that, several advanced cluster recognition routines, such as, the Early Cluster Recognition Algorithm (ECRA) [41], the Simulated Annealing Clusterization Algorithm (SACA) [42], have been put forward in recent years. For the purposes of the present exploration, however, we use the simplest phase-space coalescence model, see, e.g., refs.[34, 35], where a physical fragment is formed as a cluster of nucleons with relative momenta smaller than P_0 and relative distances smaller than R_0 . The results presented in the following are obtained with $P_0 = 263$ MeV/c and $R_0 = 3$ fm. This simple choice may thus limit the scope and importance of our study here. For instance, we shall limit ourselves to studies of the relative/differential observables for neutron-proton and t- 3 He pairs without attempting to study pairs of the heavier mirror nuclei. An extended study including the heavy mirror nuclei using the advanced coalescence and/or earlier cluster recognition methods is planned.

III. RESULTS AND DISCUSSIONS

Noticing that the FOPI π^-/π^+ data favors the symmetry energy with $x = 1$ at supra-saturation densities[21] while the NSCL/MSU isospin diffusion data favors a symmetry energy at sub-saturation densities between those with $x = 0$ and $x = -1$ [14, 15], for comparisons we use here $x = 1$ and $x = -1$ as two limits of the symmetry energy at high densities. The corresponding symmetry energy functionals are depicted in the inset of Fig. 1. They represent a typically stiff ($x = -1$) and a very soft ($x = 1$) symmetry energy at supra-saturation densities.

In the FOPI experiments[23], the π^-/π^+ ratio was measured down to a beam energy of 400 MeV/nucleon where it shows the largest sensitivity to the high-density behavior of the nuclear symmetry energy[21]. The maximum density reached in central Au+Au reactions at 400 MeV/nucleon is about $2.5\rho_0$. It is well known that pions are most abundantly produced in the central collisions. However, the π^-/π^+ ratio is almost a constant from most central to mid-central impact parameters[21]. It is also

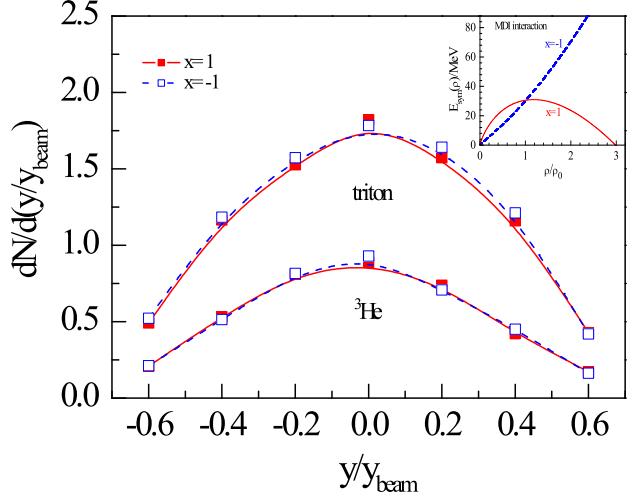


FIG. 1: Multiplicities of triton and 3 He as a function of the reduced C.M. rapidity in the reaction of $^{132}Sn + ^{124}Sn$ at a beam energy of 400 MeV/nucleon and an impact parameter of 5 fm with the symmetry energy parameter $x = 1$ (soft) and $x = -1$ (stiff), respectively.

well known that transverse collective flow is zero in head-on and grazing collisions but is the largest in mid-central collisions. Considering all of the above, as an example, we study $^{132}Sn + ^{124}Sn$ reaction at an incident beam energy of 400 MeV/nucleon and an impact parameter of 5 fm. This reaction will be available at FAIR/GSI in the near future. We note that the maximum density reached in this reaction is about $2\rho_0$.

Before we study the triton- 3 He relative and differential flows, it is necessary to first examine the yields of triton and 3 He and their ratio. Although these observables and their dependence on the symmetry energy have been studied before especially at lower incident energies, see, e.g., ref.[39, 40], they serve as useful references for measuring the symmetry energy effects on the π^-/π^+ ratio and the flow observables. Shown in Fig. 1 are the rapidity distributions of triton and 3 He for the $^{132}Sn + ^{124}Sn$ reaction at an incident energy of 400 MeV/nucleon and an impact parameter of 5 fm. It is seen that these clusters are produced mostly at mid-rapidities from the participant region. The yields, however, are not sensitive to the symmetry energy. This is not surprising. Even at much lower energies where effects of the symmetry energy is stronger, the neutron and proton yields themselves are not so sensitive to the symmetry energy as the yields are dominated by the isoscalar part of the nuclear mean field and nucleon-nucleon collisions.

At Fermi energies, the ratio of neutrons to protons or that of mirror nuclei were shown to carry more information about the symmetry energy as effects of the isoscalar potential can be largely cancelled in the ratios[22, 39, 40, 43, 44]. However, at significantly

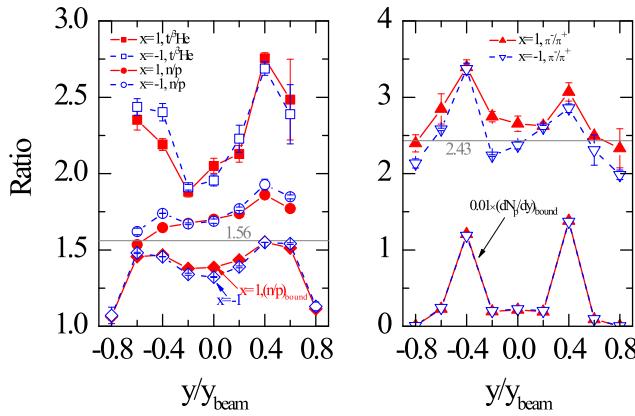


FIG. 2: Comparisons of particle ratios in the same reaction as in Fig. 1. The horizontal line at 1.56 (2.43) in the left (right) window is the reaction system's neutron/proton ratio (squared).

higher energies, e.g., 400 MeV/nucleon, except for high transverse momentum particles especially those being squeezed-out perpendicular to the reaction plane[45], the neutron to proton ratio becomes less sensitive to the symmetry energy than at lower beam energies[24, 46]. For comparisons, the $t/{}^3\text{He}$ ratio together with the free and bound neutron to proton ratios are shown in the left window of Fig. 2 for the ${}^{132}\text{Sn} + {}^{124}\text{Sn}$ reaction. Here, the bound neutrons and protons are the nucleons in the fragments with $A \geq 2$. The horizontal line at 1.56 is the reaction system's neutron/proton ratio $(N_T + N_P)/(Z_T + Z_P)$. Several interesting observations can be made here. Firstly, the $(n/p)_{\text{bound}}$ ($(n/p)_{\text{free}}$) is significantly less (higher) than the neutron/proton ratio of the reaction system. This is the well known isospin fractionation phenomenon[47, 48, 49] which is reduced here by the production of charged pions. Moreover, at mid-rapidity the $(n/p)_{\text{bound}}$ shows appreciable sensitivity to the variation of the symmetry energy. Unfortunately, both the $(n/p)_{\text{free}}$ and $t/{}^3\text{He}$ ratios show very little sensitivity to the variation of the symmetry energy within statistical error bars, except around the projectile and target rapidities of $y/y_{\text{beam}} = \pm 0.5$.

It is especially worth noting that the $t/{}^3\text{He}$ ratio is much higher than the free and bound neutron/proton ratios. A few more comments about this observation are in order here. First of all, we notice that the assumption of $t/{}^3\text{He} = (n/p)_{\text{free}}$ and that they are equal to the $(N_T + N_P)/(Z_T + Z_P)$ have been widely used in momentum-space coalescence models in the literature, especially at high energies. Our results here and also those reported earlier from transport model simulations[31, 50] indicate that the coordinate-space correlation is important in considering the cluster formation. This feature has also been observed in the parton hadronization process in ultra-relativistic heavy-ion

collisions by the quark coalescence model[51]. In fact, a similarly high $t/{}^3\text{He}$ ratio has also been observed in the experimental data of heavy-ion reactions at Fermi energies, see, e.g., ref.[31]. The possible explanations for the high n/p and $t/{}^3\text{He}$ ratios include the isospin fractionation and the overwhelmingly preferential production of symmetric light clusters such as deuteron and alpha particles[52] in these reactions. Our analyses by turning on/off the coalescence after-burner, the Coulomb and symmetry potentials indicate that both mechanism are at work. It is also interesting to mention that, at Fermi energies, using a freeze-out temperature extracted from the experiments the rather high $t/{}^3\text{He}$ ratio can also be well reproduced within a statistical model[53] assuming that the difference in the chemical potentials of triton and ${}^3\text{He}$ is dominated by their Coulomb potentials[31].

The rapidity distributions of the π^-/π^+ ratio and the bound protons are shown in the right window of Fig. 2. Interestingly, comparing the ratios of all particle-pairs shown in both windows of Fig. 2, it is obvious that the π^-/π^+ ratio shows the highest sensitivity to the symmetry energy. More quantitatively, effects of the symmetry energy on the ratio of the total yields of charged pions is about 10% by varying the x parameter from -1 to 1 . This is less than the approximately 20% effect observed in the head-on collisions between two Au nuclei at the same beam energy. This is probably because of the significantly smaller size in ${}^{132}\text{Sn} + {}^{124}\text{Sn}$ although it is more neutron-rich[54]. Moreover, by comparing the rapidity distributions of the π^-/π^+ ratio and the bound protons one sees clearly the well-known Coulomb focusing effects on the π^-/π^+ ratio, namely, more π^- 's (π^+ 's) are attracted (repelled) towards (away) from the target and projectile residues[55, 56] where most of the protons are located in the semi-central reactions considered.

We now investigate whether the transverse collective flows of triton and ${}^3\text{He}$ can be used to probe the symmetry energy. Firstly, we examine in Fig. 3 their transverse flows individually. The average C.M. transverse momentum per nucleon $\langle p_x/A \rangle$ in the reaction plane is defined as

$$\langle p_x/A \rangle (y) \equiv \frac{1}{N(y)} \sum_{i=1}^{N(y)} p_x^i / A(y) \quad (4)$$

where $N(y)$ is the total number of fragments of mass A in the rapidity bin at y . The correlation between the $\langle p_x/A \rangle$ and rapidity y reveals the transverse collective flow[57]. It is seen that ${}^3\text{He}$ clusters show a stronger flow than triton clusters. This is mainly due to the stronger Coulomb force experienced by the ${}^3\text{He}$ clusters. More interestingly, the transverse flow of ${}^3\text{He}$ clusters show appreciable sensitivity to the variation of the symmetry energy.

The transverse flow is a result of actions of several factors including the isoscalar, symmetry and Coulomb potentials and nucleon-nucleon scatterings. It is well known that the transverse flow is sensitive to the isoscalar potential. Given the remaining uncertainties associated with

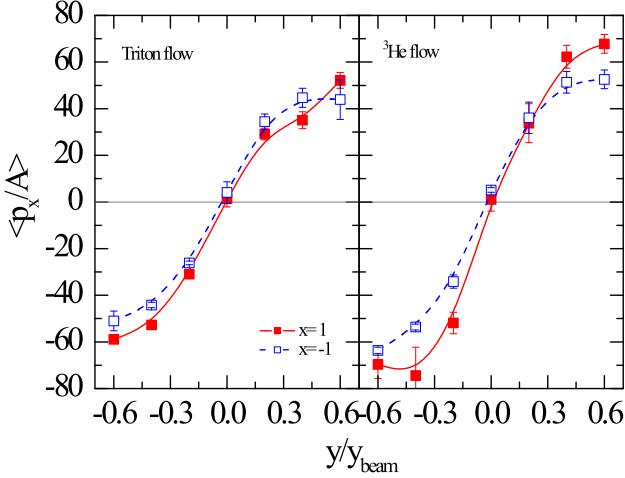


FIG. 3: Triton and ^3He transverse flows (in unit of MeV) as functions of the reduced C.M. rapidity in the same reaction as in Fig. 1.

the isoscalar potential and the small size of the symmetry energy effects, it would be very difficult to extract any reliable information about the symmetry energy from the individual flows of triton and ^3He clusters. Thus techniques of reducing effects of the isoscalar potential while enhancing effects of the isovector potential are very helpful [24, 45, 46, 58, 59]. We thus study in Fig. 4 the triton- ^3He relative and differential flows. The relative flow is given as

$$\langle p_x^t/A \rangle - \langle p_x^{^3\text{He}}/A \rangle = \frac{1}{N_t} \sum_{i=1}^{N_t} p_x^i/A - \frac{1}{N_{^3\text{He}}} \sum_{i=1}^{N_{^3\text{He}}} p_x^i/A. \quad (5)$$

The triton- ^3He differential flow reads

$$\begin{aligned} \langle p_x^{t-^3\text{He}}/A \rangle &= \frac{1}{N_t + N_{^3\text{He}}} \left(\sum_{i=1}^{N_t} p_x^i/A - \sum_{i=1}^{N_{^3\text{He}}} p_x^i/A \right) \\ &= \frac{N_t}{N_t + N_{^3\text{He}}} \langle p_x^t/A \rangle - \frac{N_{^3\text{He}}}{N_t + N_{^3\text{He}}} \langle p_x^{^3\text{He}}/A \rangle, \end{aligned} \quad (6)$$

where N_t , $N_{^3\text{He}}$ are the number of triton and ^3He in the rapidity bin at y . From the upper panel of Fig. 4, it is seen that the triton- ^3He relative flow is very sensitive to the symmetry energy. Because of the larger slope of the ^3He flow, the triton- ^3He relative flow shows a negative slope at mid-rapidity. Effects of the symmetry energy on the differential flow shown in the lower panel, however, is relatively small. Although the ^3He flow is more sensitive to the symmetry energy, the small number of ^3He clusters (as shown in Fig. 1) makes the ^3He flow contributes less to the triton- ^3He differential flow (as indicated in Eq. (6)). The triton- ^3He differential flow is therefore dominated by triton clusters. Consequently, it is less sensitive to the symmetry energy than the triton- ^3He relative

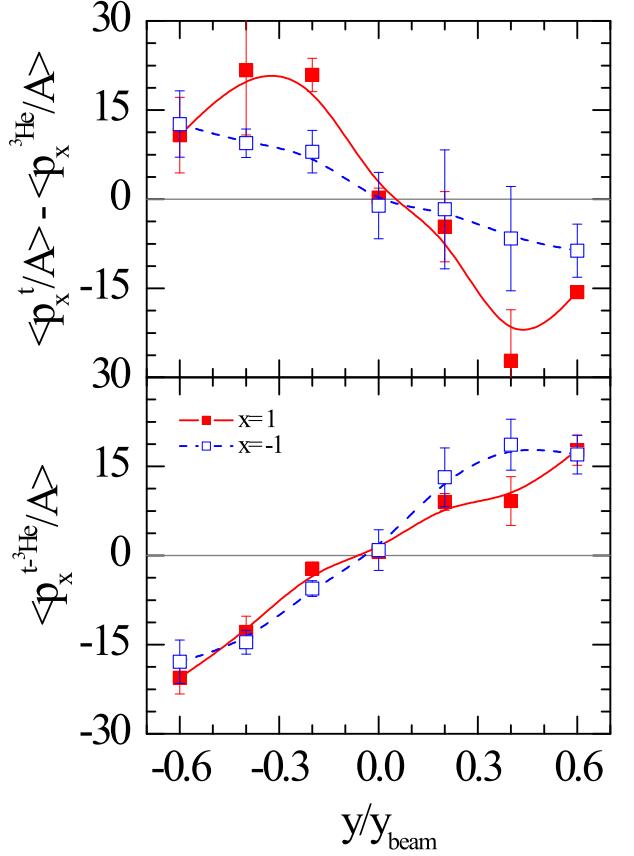


FIG. 4: Triton- ^3He relative and differential flows (in unit of MeV) as a function of the reduced C.M. rapidity in the same reaction as in Fig. 1.

flow. The slope $F(x) \equiv d \langle p_x/A \rangle / d(y/y_{beam})$ of the transverse flow at mid-rapidity can be used to characterize more quantitative the symmetry energy effects. We found that for the t- ^3He relative flow, $F(x=1) \approx -74$ MeV/c and $F(x=-1) \approx -22$ MeV/c, respectively. For the t- ^3He differential flow, $F(x=1) \approx 21$ MeV/c and $F(x=-1) \approx 42$ MeV/c, respectively. Compared to the π^-/π^+ ratio in the same reaction, the symmetry energy effects on the t- ^3He relative and differential flows are much stronger. Thus, especially the t- ^3He relative flow can be used as a very useful and independent tool to test the soft symmetry energy at supra-saturation densities extracted from studying the π^-/π^+ ratio[21].

For comparisons, we now study the relative and differential flows for free neutron-proton pairs in Fig. 5. It is seen that they have the same features as the relative and differential flows for triton- ^3He pairs. The larger symmetry energy effects at positive rapidities are due to the more neutron-rich of projectile. More quantitatively, in terms of the slope parameter F , for the n-p relative flow, $F(x=1) \approx -53$ MeV/c and $F(x=-1) \approx -25$ MeV/c,

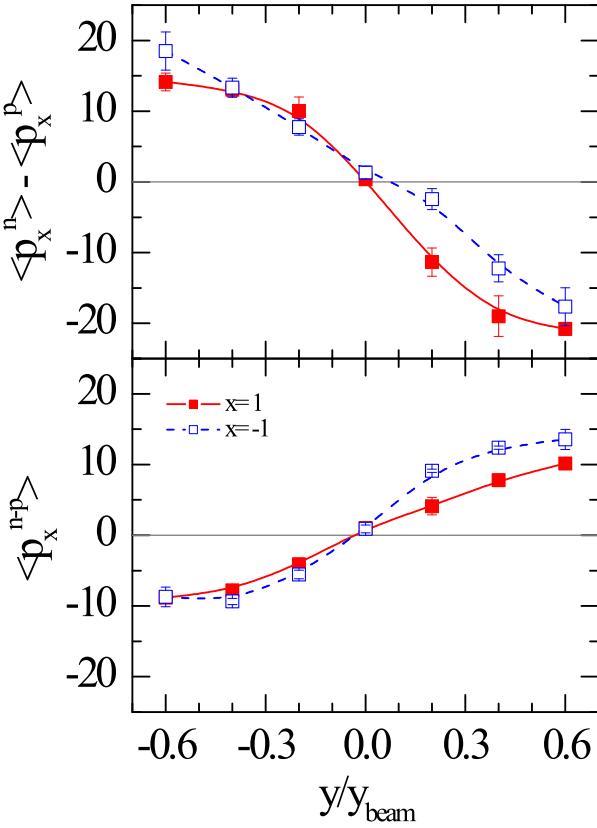


FIG. 5: Neutron-proton relative and differential flows (in unit of MeV) as a function of the reduced C.M. rapidity in the same reaction as in Fig. 1.

respectively. For the n-p differential flow, $F(x = 1) \approx 20$ MeV/c and $F(x = -1) \approx 36$ MeV/c, respectively. Com-

paring the results in Figs. 5 and 4 and the slope parameters F for t - 3 He and neutron-proton pairs, we can conclude that they are almost equally useful for probing the density dependence of the nuclear symmetry energy.

IV. SUMMARY

In summary, using a hybrid approach coupling the transport model IBUU04 to a phase-space coalescence after-burner we studied the t - 3 He relative and differential flows in semi-central $^{132}Sn + ^{124}Sn$ reactions at an incident energy of 400 MeV/nucleon. We found that the nuclear symmetry energy affects more strongly the t - 3 He relative and differential flows than the π^-/π^+ ratio in the same reaction. The t - 3 He relative flow can be used as a particular powerful probe of the high-density behavior of the nuclear symmetry energy. It can be used to test the indications about the symmetry energy at supra-saturation densities observed in the analysis of the π^-/π^+ data from heavy-ion reactions.

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